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Structure and magnetic properties of the Co_2FeAl and Co_2NiSi Heusler alloy films

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Abstract. The structural and magnetic properties (field dependences of the magnetization in magnetic fields of up to 6 kOe) of thin-film Co_2FeAl, and Co_2NiSi Heusler alloys grown by pulsed laser deposition on glass and a single-crystalline Al_2O_3 R-plane substrate at different growth temperatures (20, 280 and 420 °C) were studied. It was found that the stoichiometric composition of the films depends on the substrate temperature during growth and repeats the composition of the target for films grown at low temperatures. The films deposited on a single crystalline Al_2O_3 substrate have uniaxial magnetic anisotropy in the plane.

1. Introduction

The progress of modern nanoelectronics and spintronics requires the search and creation of new magnetic materials with high spin polarization of charge carriers. The corresponding materials should have high Curie temperatures T_C because spintronic devices will mainly be used near the room temperature. Many of Heusler alloys, for example Co_2YSi and Co_2YAl (Y = Ti, V, Cr, Mn, Fe, Co, Ni) are known to be half-metallic ferromagnets [1 - 4], in which the electronic spectrum at the Fermi level E_F has an energy gap for one of the spin directions and its absence for another one. Therefore 100% spin-polarization can be realized at E_F. For this reason, it is of interest to use these alloys in spintronics for creating instruments based on the magnetic tunneling and giant magnetoresistance effects, as a spin as spin-polarized electron injectors in structures switchable by a spin-polarized current and in magnetic transitions, where, as was shown [5], the spin nonequilibrium of conduction electrons due to injection leads to radiative electron transitions between spin subbands. Thus, it is possible to create a laser operating in the THz range at room temperature. Such device can be created using planar (film) technology. Therefore, the study of the properties of films and film structures is an important part of such researches. And epitaxy processes can provide additional benefits to such materials. In our previous papers [6, 7] the films of Fe_2CoAl and Co_2FeAl Heusler alloys grown on the R-plane sapphire substrate were studied using scanning atomic and magnetic force microscopies, supplemented with measurements of film magnetoresistance. Nonmonotonic dependences of the films' morphological and magnetic properties on their growth temperature were obtained. The dependencies found were caused, as assumed, by the formation of some disordered phase at temperatures in some ranges of the growth temperatures where biaxial magnetic anisotropy found. A more ordered phase was grown in the other temperature ranges, in which there was the uniaxial magnetic anisotropy.

In this paper the structural and magnetic properties (field dependences of the magnetization in magnetic fields of up to 6 kOe) of thin-film Co_2FeAl (CFA) and Co_2NiSi (CNS) Heusler alloys grown by pulsed laser deposition on glass and a single-crystal Al_2O_3 R-plane substrate at different growth temperatures (20, 280 and 420 °C) were studied. The use of these films in magnetic transitions can increase the intensity of spin-injection THz radiation when current flows through them.

2. Experimental

The Co_2FeAl and Co_2NiSi Heusler alloy films were grown by pulsed laser deposition in an ultrahigh basic vacuum 10^{-10} Torr on glass and a single-crystalline Al_2O_3 (-1012) R-plane substrate. Growth temperatures were 20 °C (substrate pre-annealed at 280 °C), 280 °C, and 420 °C for CFA and CNS respectively. A pulse Q-switch solid-state (AY:Nd^{+3}) laser with the wavelength 1.079 μm, 15 ns pulse duration, 10 Hz pulse frequency, and till 0.4 J radiation energy per pulse was used for target ablation. See [8, 9] for details. Elemental analysis was carried out by using a scanning electron microscope equipped with an EDAX X-ray microanalysis attachment. The structural analysis was performed at the Collaborative Access Center, M.N. Mikheev Institute of Metal Physics. X-ray diffraction studies were carried out at DRON-3M diffractometer using $\theta - 2\theta$ and ω-scans. The thickness of the films studied by the X-ray diffraction was over 100 nm. The field dependencies of the magnetization M (H) were measured at room temperature in magnetic fields of up to 6 kOe applied along normal and parallel to the film planes.

3. Results and discussion

The results on the X-ray microanalysis are shown in the Tables 1 and 2. Small amount of target drops is seen on film surfaces. They are not affecting on average composition. However, the presence of droplets allows one to compare the stoichiometric composition of the target and the accuracy of transfer and preservation of the composition of the target in the film. It can be clearly seen that for CFA films at low temperatures of 20 °C and 280 °C, the composition of the target corresponds quite well to the composition of the film. At a higher temperature of 420 °C, the film has an approximate composition of $Co_{2.21}Fe_{1.27}Al_{0.52}$, i.e. a significant aluminum deficiency is observed in the film. This means that such a temperature, taking into account the not too high melting point of aluminum, creates conditions for the re-evaporation of high-energy particles after laser evaporation and is excessive for the correct accommodation of aluminum atoms in the lattice of the Heusler alloy. For the CNS alloy, there is no such problem at all three temperatures studied, since the boiling and melting temperatures of all three components included in the alloy are close and the elemental composition of the target is transferred from the film quite well.

Results of the X-ray diffraction studies show that there is only one peak in XRD patterns obtained for Co_2FeAl films grown on a glass substrate at 20 °C and at 280 °C. It was identified as (220) of $L2_1$ structure. The texture investigation demonstrates the <220> texture. The full width at half maximum of the rocking curve (ω-scan) was 6 degs and 18 degs for the Co_2FeAl films grown at 20 °C and 280 °C respectively. Diffraction patterns of CNS films grown on the sapphire substrate show peaks only from the sapphire. This result can be due to the tilted epitaxy of the film when the main reflex is tilted a few degrees from the normal to the film surface It is not related to the vicinal surface of the substrate but is a specific result of stress relaxation in the growing epitaxial film. The phenomenon is very characteristic of the R- plane of the sapphire [10]. Film thicknesses of CNS grown at 20 °C and at 280 °C are 36.6 nm and 64 nm, correspondingly.

The field dependencies of sample magnetization are shown in figure 1. It is seen that hard axis and easy axis have differences in films grown at higher temperatures. It means that films CFA and CNS become anisotropic at 280 °C and 420 °C, correspondingly. At that time the CFA and CNS films grown at 20 °C and also CNS films grown at 280 °C are seem to be magnetically isotropic. The shape of the field dependencies is similar to that found in the paper [11]. The values of the coercive fields H_c

obtained from the field dependences of the magnetization of the samples are presented in Table 3. It can be seen from the table that with the growth temperature increase, the coercive field for the CFA alloy grown on glass decreases. At the same time, the dependence of the coercive field on the growth temperature for CNS films is nonmonotonic. Small values of the coercive field for textured CFA films grown at 280 °C and 420 °C indicate a small number of defects in these films despite a change in the composition of films grown at 420 °C.

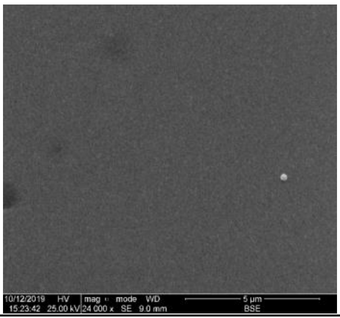
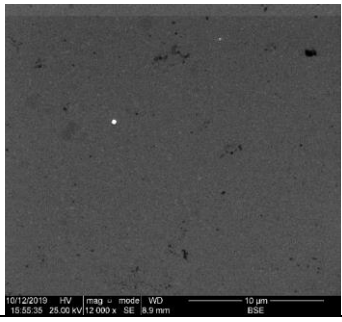
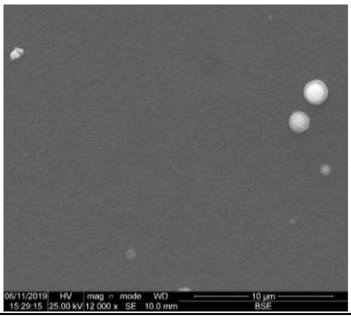
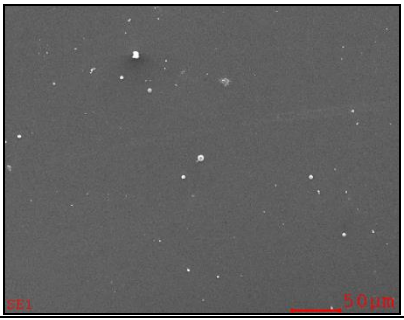
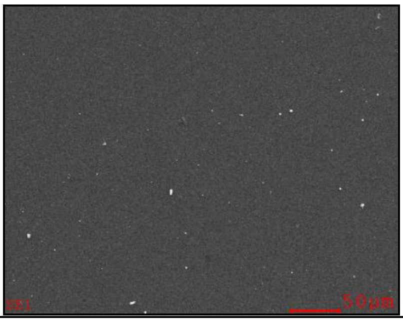
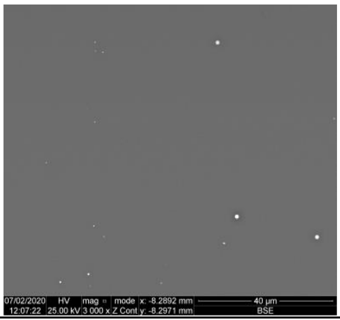
Table 1. The element analysis of Co_2FeAl films grown at different temperatures.		
20°C	280°C	420 °C
		
Average composition		
$Co_{1.89}Fe_{0.94}Al_{1.17}$	$Co_{1.93}Fe_{1.05}Al_{1.02}$	$Co_{2.21}Fe_{1.27}Al_{0.52}$
Target drop		
$Co_{1.82}Fe_{0.80}Al_{1.38}$	$Co_{2.04}Fe_{1.03}Al_{0.93}$	Co_2FeAl

Table 2. The elemental analysis of Co_2NiSi films grown at different temperatures.		
20 °C	280 °C	420 °C
		
Average composition		
$Co_{1.7}Ni_{0.9}Si_{1.4}$	$Co_{1.88}Ni_{0.84}Si_{1.28}$ is averaged with drops $Co_2Ni_{0.9}Si_{1.09}$ is averaged without drops	$Co_{1.78}Ni_{0.83}Si_{1.39}$ is averaged with drops $Co_{1.84}Ni_{0.83}Si_{1.33}$ is averaged without drops
Target drop		
$Co_{1.77}Ni_{0.98}Si_{1.25}$	$Co_{1.6}Ni_{0.94}Si_{1.46}$	$Co_{1.91}Ni_{0.99}Si_{1.1}$

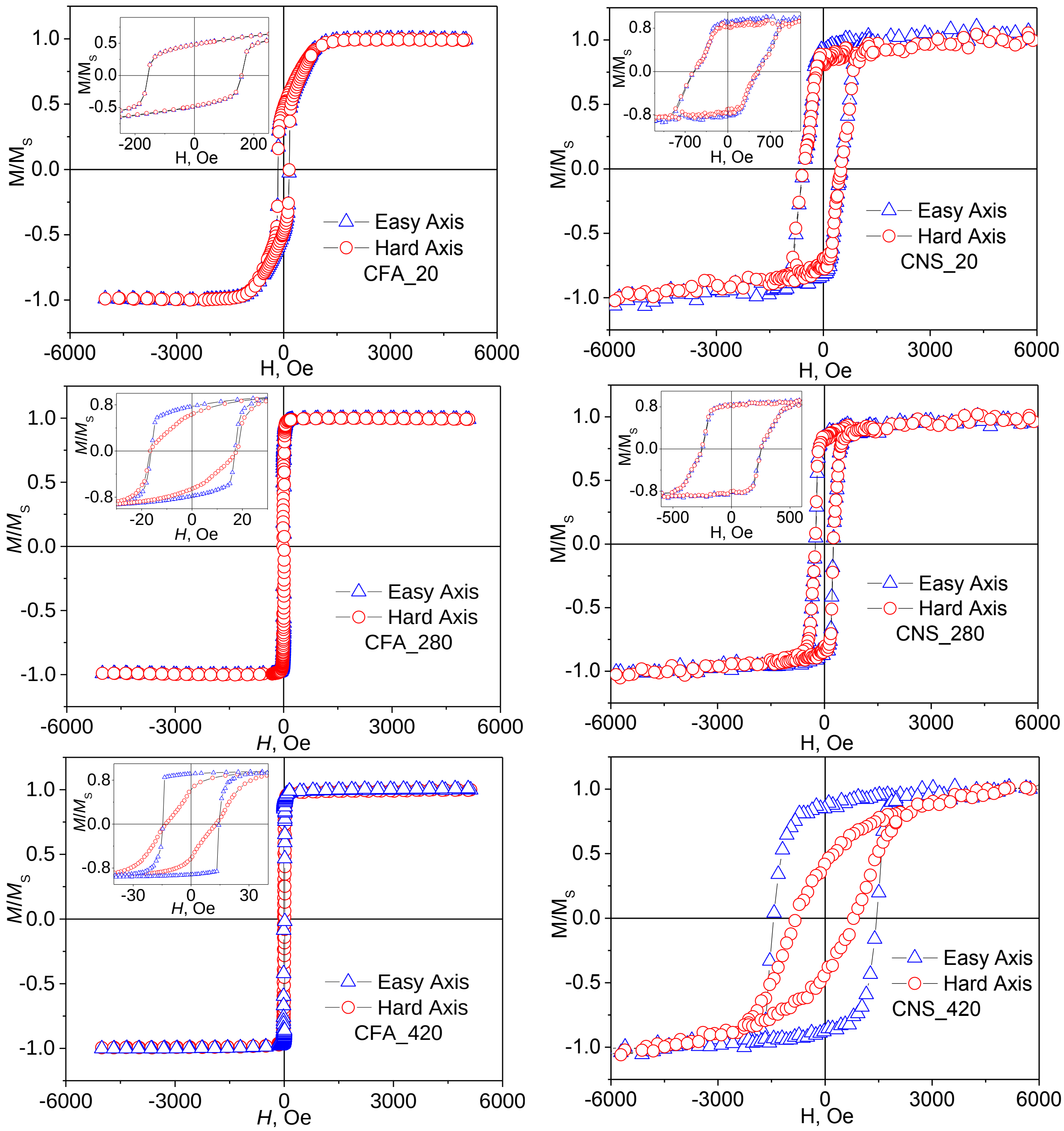


Figure 1. Field dependencies of magnetization.

Table 3. The coercive fields of Co_2FeAl and Co_2NiSi films.

Sample	H_C, Oe	Sample	H_C, Oe
Co_2FeAl, 20°C	157	Co_2NiSi, 20°C	520
Co_2FeAl, 280°C	17	Co_2NiSi, 280°C	253
Co_2FeAl, 420°C	14	Co_2NiSi, 420°C	1438/816

The value of H_c for CFA films decreases with increasing temperature from 157 Oe at 20 °C to 14 Oe at 420 °C. This means that the number of defects in the film decreases and the crystal structure of the alloy becomes more perfect. For CNS films, the situation is completely different. The relatively large value of H_c for films grown at room temperature with an increase in the growth temperature initially decreases more than twice, and for a film grown at 420 °C it increases sharply and becomes substantially anisotropic. Large values of the coercive field for CNS films grown at 420 °C are possibly associated with the precipitation of a new nanophase during growth at high temperature [12].

4. Conclusion

The structural and magnetic properties of thin-film Co_2FeAl, and Co_2NiSi Heusler alloys grown by pulsed laser deposition on glass and a single-crystalline Al_2O_3 R-plane substrate at different growth temperatures (20, 280and 420 °C) were studied. It was found that the stoichiometric composition of the films depends on the substrate temperature during growth and repeats the composition of the target for films grown at low temperatures. The films become magnetically anisotropic at high growth temperatures and have relatively low coercive field (except Co_2NiSi grown at 420 °C). Apparently, the use of these films in magnetic transitions can increase the intensity of spin-injection THz radiation when current flows through them.

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